

## Reliability and Other Space-Related Characterizations of Polymer Aluminum Capacitors

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### Abstract

A study on the physical and electrical characterizations of polymer aluminum (PA) capacitors revealed three physical structures: traditional wound, stacked, and laminated. Although most of the PA capacitors exhibited high capacitance and m $\Omega$ -level ESR values regardless of their structure, the electrical performance of other PA capacitors was found to be highly dependent on capacitor structure. PA capacitors made with a traditional wound structure show high dielectric loss, high DC leakage current, low capacitance roll-off frequency, and low surge breakdown voltages. PA capacitors with a laminated structure exhibit the most stable dielectric response versus frequency and temperature. PA capacitors with a stacked structure exhibit a comparable electrical performance but can be built with higher voltage rating.

In this study, only PA capacitors with stacked and laminated structures were evaluated for reliability, outgassing, and electrical characterization before and after thermal vacuum cycling. A Ta polymer capacitor was also included in all characterizations as a baseline control.

Highly accelerated testing (HAT) shows that PA capacitors have a use-level calculated mean time-to-failure of more than 10<sup>6</sup> years. The temperature accelerating factor appears to be similar for both PA and Ta polymer capacitors. The voltage accelerating factor of PA capacitors, on the other hand, appears to be higher than that of Ta polymer capacitors.

The test results clearly show that this sample of PA capacitors meets the criteria for outgassing acceptance. Thermal vacuum cycling did not impact the PA capacitors' electrical performance.

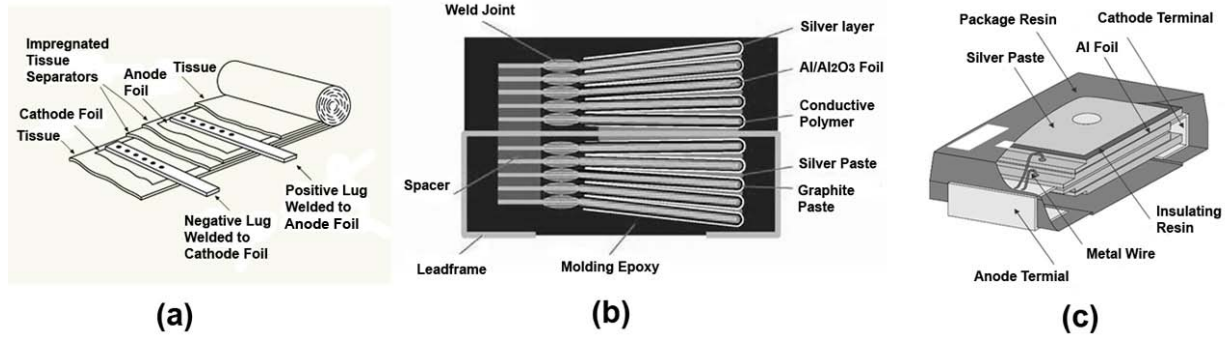
### Introduction

Polymer aluminum (PA) capacitors from several manufacturers, with various combinations of capacitance, rated voltage, and equivalent series resistance (ESR) values, were physically examined and electrically characterized. A physical construction analysis of the capacitors revealed three different capacitor structures, as shown in Figure 1.

The three structures include: (a) *traditional wound*: rolled foil with a conducting polymer replacing the wet electrolyte, and the structure has a loose winding with gaps between foil; (b) *stacked*: a number of etched and anodized aluminum foils are stacked and welded together to form an anode terminal. The cathode was constructed with a coating of silver epoxy and graphite paste; (c) *laminated*: two layers of thick aluminum foils are wire-bonded to a lead frame for the anode construction, and the cathode is formed with silver epoxy connected via through holes to a plate of nickel-plated copper.

Although most PA capacitors exhibit high capacitance and m $\Omega$ -level low ESR values regardless of capacitor structure, other electrical characteristics are highly dependent on the capacitor structure. PA capacitors made with a loose wound structure show high dielectric loss, high DC leakage current, low capacitance roll-off frequency, and

low surge breakdown voltages. Capacitors with a laminated structure exhibit the most stable dielectric response versus frequency and temperature. On the other hand, PA capacitors with a stacked structure exhibit a comparable electrical performance but can be built with higher voltage rating [1].



**Figure 1.** Physical construction analysis of PA capacitors revealed three different capacitor structures: (a) traditional wound, (b) stacked, and (c) laminated.

A destructive surge step stress test (SSST) was applied to PA capacitors to reveal the voltage breakdown and failure mechanisms under time-varying stress. The SSST results clearly suggest that these PA capacitors share a similar failure mechanism and similar voltage accelerating factors. The SSST data of PA capacitors also reveal that the dielectric breakdown voltage under an SSST exhibits very tight and predictable time-to-failure distributions [2]. Similar results were also previously reported by other researchers [3].

In this study, further efforts are made to evaluate the reliability and other space-related characterizations of PA capacitors, such as outgassing and thermal vacuum testing. However, based on the results of previous studies, only PA capacitors with stacked and laminated structures were selected for this evaluation.

### Reliability Evaluation of Polymer Aluminum Capacitors

The detail characteristics of PA capacitors from several manufacturers, with various combinations of capacitance and construction, are summarized in Table I. A Ta polymer capacitor (KTA22060) is also included as a baseline control for the purpose of comparison. All of the capacitors are subjected to highly accelerated testing (HAT) for the reliability evaluations.

**Table I.** Characteristics of Polymer Capacitors for HAT

Sample ID	Cap ( $\mu$ F)	Rated Voltage ( $V_r$ )	ESR ( $m\Omega$ )	Cathode	Construction	Mfr.
PA18063	180	6.3	5	Al-Polymer	Stacked	A
KTA22060	220	6.0	9	Ta-Polymer	N/A	D
KA10012	100	12.0	15	Al-Polymer	Stacked	D
RA10060	100	6.0	5	Al-Polymer	Laminated	E

For capacitors, the applied stresses are usually the voltage and temperature, and they are normally held constant during the testing. For a wide class of failure modes, the failure rate at one temperature  $T_1$  is related to the failure rate at a second temperature  $T_2$  by an Arrhenius relation:

$$A_T = \frac{Rate(T_1)}{Rate(T_2)} = e^{-\left(E_s/k_B\right)\left(\frac{1}{T_1} - \frac{1}{T_2}\right)} \quad (1)$$

where  $A_T$  is the temperature acceleration factor,  $E_s$  is an activation energy,  $k_B$  is the Boltzman constant, and the temperatures are measured on an absolute scale.

Empirical work has often found that the applied voltage changes the failure rate following an inverse power law:

$$A_V = \frac{\text{Rate}(V_1)}{\text{Rate}(V_2)} = \left(\frac{V_2}{V_1}\right)^n \quad (2)$$

where  $A_V$  is the voltage acceleration factor and  $n$  is an empirical parameter. Prokopowicz and Vaskas have proposed that the rate of failure caused by a single failure mode when both  $V$  and  $T$  are changed is the product of the separate acceleration factors:

$$A_{VT} = \frac{\text{Rate}(T_1)}{\text{Rate}(T_2)} \cdot \frac{\text{Rate}(V_1)}{\text{Rate}(V_2)} = \left(\frac{V_2}{V_1}\right)^n \cdot e^{-(E_S/K_B)\left(\frac{1}{T_1} - \frac{1}{T_2}\right)}. \quad (3)$$

Equation 3 has proven useful in the capacitor industry for testing multilayer ceramic capacitors at various test conditions. An average of  $n \sim 3$  has generally been found for the voltage acceleration factor, and an average value of  $1 < E_S < 2$  eV is typical for the temperature acceleration factor of ceramic capacitors [4].

When a 2-parameter Weibull model is applied, the reliability at time  $t$  is given by:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^\beta} \quad (4)$$

where  $e$  is the base for natural logarithms,  $t$  the failure time, slope  $\beta$  is the dimensionless shape parameter whose value is often characteristic of the particular failure mode under study, and  $\eta$  is the scale parameter that represents the point at which 63.2% of the population has failed and that is related to all other characteristic times, such as mean time-to-failure (MTTF):

$$MTTF = \eta \Gamma(1 + 1/\beta), \quad (5)$$

where  $\Gamma(x)$  is the gamma function of  $x$ . (Note, for example, that  $\Gamma(1 + 1/\beta)$  ranges from 0.887 to 0.900 as  $\beta$  ranges from 2.5 to 3.5.)

When both  $A_V$  and  $A_T$  are combined for HAT, the Weibull distribution scale parameter  $\eta$  can be expressed as:

$$\eta(V, T) = \frac{C}{V^n} \cdot e^{\left(\frac{B}{T}\right)} \quad (6)$$

where  $C$  and  $B = E_S/k_B$  are constants. When Equations 4, 5, and 6 are combined, the reliability at time  $t$   $R(t)$  and  $MTTF$  can be expressed as:

$$R(t) = e^{-\left(\frac{t V^n e^{-\left(\frac{B}{T}\right)}}{C}\right)^\beta} \quad (7)$$

and

$$MTTF = \frac{C}{V^n} \cdot e^{(B/T)} \Gamma(1 + 1/\beta). \quad (8)$$

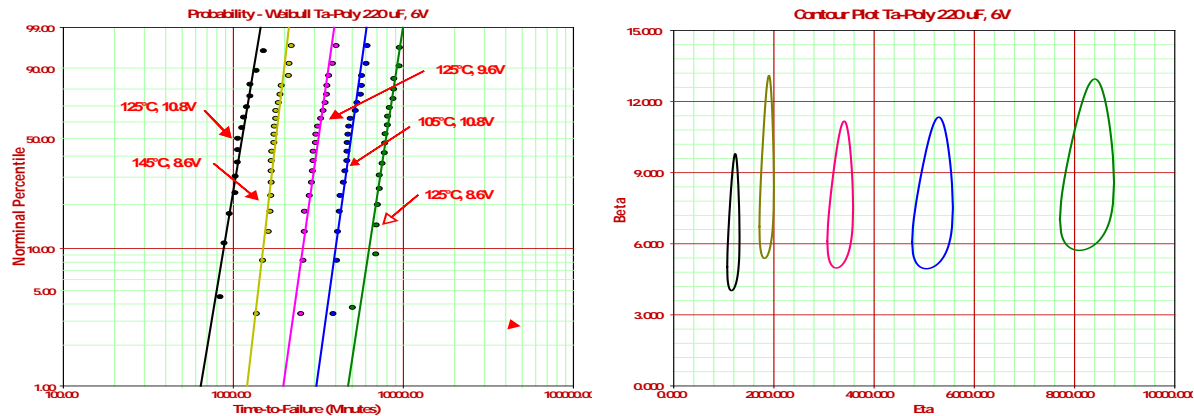
By taking advantage of the maximum likelihood estimation method, reliability and accelerating parameters  $B$ ,  $\beta$ ,  $C$ , and  $n$  in Equation 7 can all be determined [7].

**Table II.** HAT Conditions Used in This Study

Temperature (°C)	Voltage Level 1	Voltage Level 2	Voltage Level 3
105		1.8Vr	
125	1.4Vr	1.6Vr	1.8Vr
145		1.4Vr	

All polymer capacitors were HAT tested at three accelerated stress levels for temperature and voltage, as shown in Table II, where  $V_r$  is the rated voltage of a capacitor sample.

Figure 2 shows the cumulative failure rate as a function of time-to-failure on a Weibull plot for a 220  $\mu\text{F}$ , 6 V Ta polymer capacitor from manufacturer D (KTA22060). The test conditions for each HAT data set are labeled for temperature and voltage. The corresponding contour plot is also illustrated in Figure 2 (right), which reveals that all of the contours are well separated, with no obvious crossovers, indicating an acceptable accelerated testing profile. When a horizontal line is drawn between  $6.0 < \beta < 9.0$ , it appears to cross all contours, indicating that the data sets obtained at different stress levels share a single failure mode.



**Figure 2.** Weibull plot of failure percentile as a function of time-to-failure (left) and corresponding contour plot (right) for a 220  $\mu\text{F}$ , 6 V tantalum polymer capacitor made by manufacturer D. All of the contours are well separated, with no crossovers, indicating an acceptable accelerated testing profile from Table II.

The purpose of HAT is to predict the median life of capacitors under a normal, non-accelerated operating condition. In this study, the “normal use-level” condition refers to the capacitors being at room temperature (300K) and at rated voltage. When accelerating factors  $n$  and  $B = E_s/k_B$  are known, the reliable life  $t_R$  of a unit for a specified reliability, starting the mission at zero, can be determined by:

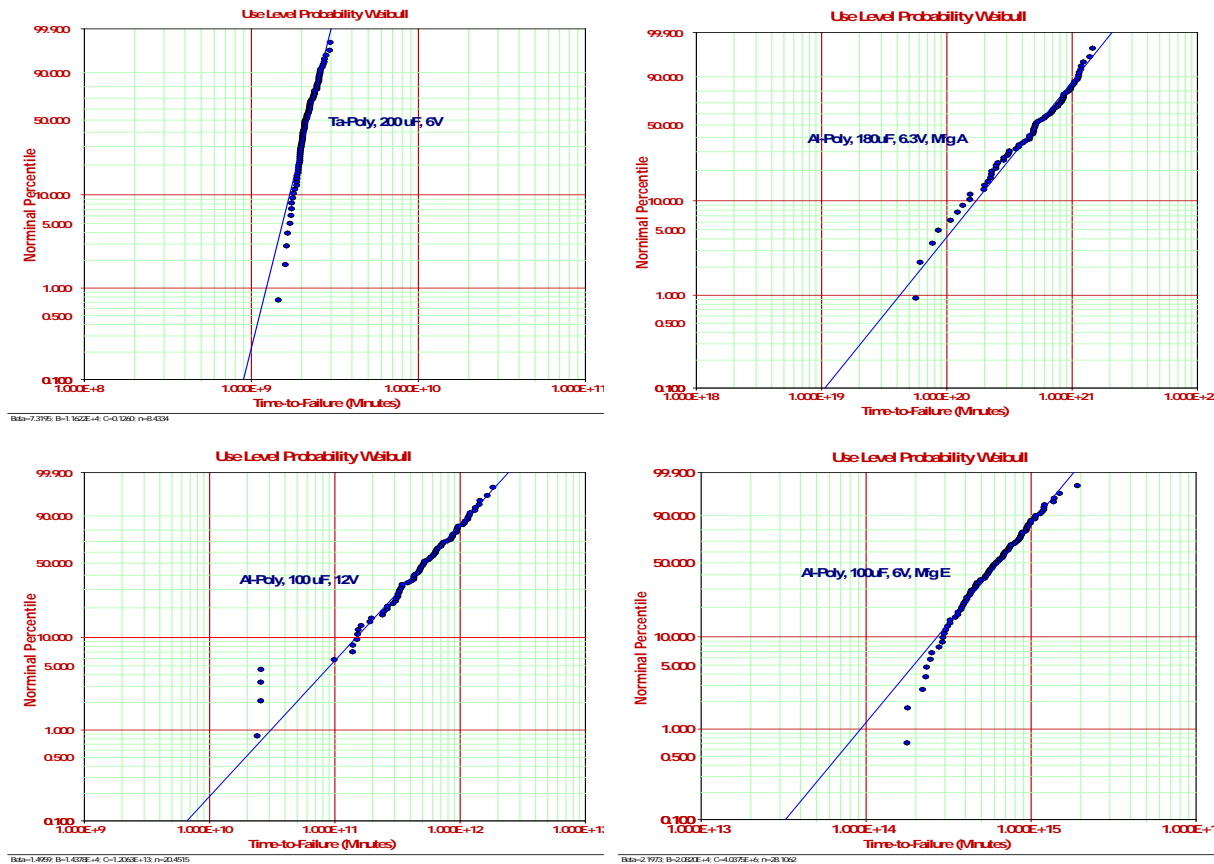
$$t_R = \eta \{-\ln[1 - F(t_R)]\}^{1/\beta} = \frac{C}{V^n} \cdot e^{(B/T)} \cdot \left\{ -\ln \left[ e^{-\left( \frac{t_R \cdot V^n \cdot e^{-(B/T)}}{C} \right)^\beta} \right] \right\}^{1/\beta} \quad (9)$$

Note that this is the life for which the unit will function successfully with a reliability of  $[1 - F(t_R)]$ . If  $[1 - F(t_R)] = 0.5$ , then  $t_R$  = the median life.

Figure 3 shows use-level Weibull probability plots of the four polymer capacitors that underwent HAT in this study. Each data point shown in Figure 2 was extrapolated using Equation 9. This was done for each failure and for any suspensions that were entered, and then the median ranks of the failures were determined. The data points were “best fitted” using a single 2-parameter Weibull model, based on the assumption that only one failure mode should be dominant in a valid HAT test. More details on this approach to characterize HAT results have been described previously [4].

Table III summarizes the Weibull reliability data, temperature accelerating factor  $E_s$ , and voltage accelerating factor  $n$  of the polymer capacitors shown in Figure 3. The MTTF data for each capacitor sample are also calculated using Equation 9. These results have revealed some interesting behaviors for polymer capacitors.

First, the Weibull slope parameter  $\beta \sim 7.32$  is much higher than that of PA capacitors, which have a typical  $\beta$  value around 1.5~2.2. This clearly suggests that Ta polymer capacitors have a different failure mode than PA capacitors.



**Figure 3.** Use-level Weibull probability plots of polymer capacitors in Table I. All data points are extrapolated using Equation 9 and best fitted using a single 2-parameter Weibull model. Upper left: 220  $\mu\text{F}$ , 6 V, Ta-Poly, manufacturer D; upper right: 180  $\mu\text{F}$ , 6.3 V, Al-Poly, manufacturer A; lower left: 100  $\mu\text{F}$ , 12 V, Al-Poly, manufacturer D; lower right: 100  $\mu\text{F}$ , 6 V, Al-Poly, manufacturer E.

The high value of  $\beta$  indicates a rapid wearout failure mode in Ta polymer capacitors. The much smaller  $\beta$  values for PA capacitors indicate a slow wearout failure mode.

Next, the temperature accelerating factor  $E_s$  appears to be similar for Ta polymer and PA capacitors, indicating a similar impact for temperature on the reliability of polymer capacitors. The results are also consistent with previous reports for Ta polymer capacitors. However, the voltage accelerating factors  $n$  of PA capacitors are found to be much higher than that of Ta polymers in this study; they are comparable to those reported previously for Ta polymers using a lognormal statistic model [5].

A higher voltage accelerating factor usually means that the capacitor's reliability is more closely dependent on the applied voltage. Although the previous study showed that no voltage de-rating is necessary for PA capacitors, the very high voltage accelerating factors are still good news for high-reliability applications [3]. This is because a

**Table III.** Weibull Modeling Results of Polymer Capacitors

Sample ID	Cap ( $\mu\text{F}$ )	Rated Voltage ( $V_r$ )	Cathode	Construction	Mfr.	Slope $\beta$	Voltage Accelerating factor ( $n$ )	$E_s$ (eV)	Use-Level MTTF (yrs.)
PA18063	180	6.3	Al-Polymer	Stacked	A	1.675	31.79	1.18	1.12E+11
KTA22060	220	6.0	Ta-Polymer	N/A	D	7.320	8.43	1.10	4.11E+4
KA10012	100	12.0	Al-Polymer	Stacked	D	1.496	20.52	1.24	1.15E+6
RA10060	100	6.0	Al-Polymer	Laminated	E	2.197	28.11	1.79	1.27E+9

significant amount of extra life reliability can be obtained if a PA capacitor with a high  $n$  value is slightly voltage de-rated.

Finally, the calculated use-level  $MTTF$  is at least  $10^4$  years for Ta-poly capacitors and  $10^6$  years for PA capacitors. Both may be good enough for most space-level applications.

### Outgassing Testing of Polymer Capacitors

Outgassing is the release of a gas that was dissolved, trapped, frozen, or absorbed in some material(s). Outgassing is a challenge for creating and maintaining clean high-vacuum environments. NASA maintains a list of low-outgassing materials to be used for spacecraft [6], as outgassing products can condense onto optical elements, thermal radiators, or solar cells and can obscure them. In addition, some materials not normally considered absorbent can release enough lightweight molecules to interfere with industrial or scientific vacuum processes. Moisture, sealants, lubricants, and adhesives are the most common sources of outgassing.

When polymer capacitors are considered for potential space applications, outgassing from these polymer materials may be a concern. It is thus important to evaluate how much volatile material will be released from these polymer capacitors when they are exposed to a space environment.

An outgassing test method was defined in American Society of Testing and Materials (ASTM) standard E595-93. A European Space Agency (ESA)-equivalent document is ECSS-Q-70-02A. Both documents describe a similar test method that covers a screening technique for determining the volatile content of materials when they are exposed to a vacuum environment. Two parameters are measured: total mass loss (TML), and collected volatile condensable materials (CVCN). An additional parameter, the amount of water vapor regained (WVR), can also be obtained after completion of the exposures and measurements required for TML and CVCN.

The outgassing test method requires related operating procedures for evaluating the mass loss of materials being subjected to  $125^\circ\text{C}$  at less than  $5 \times 10^{-5}$  Torr for 24 hours. The criteria used for the acceptance and rejection of materials shall be determined by the user and shall be based upon specific component and system requirements. In general, TML of 1.00 % and CVCN of 0.10 % have been used as screening levels for rejection of spacecraft materials.

In actual outgassing testing, three specimens were processed for each capacitor part number. All specimens were destroyed and all termination metals were removed prior to testing. The test procedure follows ASTM E595-93, paragraph 8. Table IV summarizes the testing conditions and outgassing test results for all polymer capacitors tested in this study. The results clearly show that all polymer capacitors meet the criteria for acceptance. There is no difference between Ta polymers and PA capacitors with respect to the degree of outgassing.

**Table IV.** Outgassing Test Results of Polymer Capacitors

Sample ID	Cap ( $\mu\text{F}$ )	Rated Voltage ( $V_r$ )	Cathode	TML (<1.00%)			CVCN (<0.10%)		
Test Conditions: $124.7^\circ\text{C}$ , $1.5 \times 10^{-5}$ Torr, 24 hours				#1	#2	#3	#1	#2	#3
PA18063	180	6.3	Al-Polymer	0.24%	0.22%	0.19%	0.01%	0.02%	0.01%
KTA22060	220	6.0	Ta-Polymer	0.21%	0.21%	0.20%	0.01%	0.00%	0.00%
KA10012	100	12.0	Al-Polymer	0.34%	0.41%	0.31%	0.00%	0.01%	0.00%
RA15040	150	4.0	Al-Polymer	0.33%	0.34%	0.38%	0.01%	0.01%	0.01%

### Electrical Properties Before and After Thermal Vacuum Testing

Thermal vacuum testing is a thermal cycling test that is performed at low pressures ( $10^{-4}$  Torr typical). In general, the thermal vacuum test imposes an environment that simulates orbital conditions more accurately than any other ground test. A thermal vacuum test helps to screen for the defects that are detectable by a thermal cycle test, as well as for the defects that would respond only to a vacuum environment.

According to MIL-STD-1540, all high-orbit systems and vehicles are required to undergo thermal vacuum testing. MIL-HDBK-340 and NASA standard GSFC-STD-7000 define the test level and duration not only for systems and

vehicles, but also for subsystem and unit levels. Based on the guidelines in MIL-HDBK-340A, Vol. 1 and GSFC-STD-7000, a thermal vacuum cycling profile was determined. This profile is shown in Figure 4.

All capacitors were visually inspected and electrically tested for capacitance, dielectric loss (df), ESR, and DC leakage per MIL-PRF-55365G before and after thermal vacuum testing. All testing data are presented in a statistic Weibull plot format, as shown in Figure 5.

The capacitance and DC leakage do not appear to change after thermal vacuum testing, whereas df and ESR show a slight decrease after testing. The decreases in df and ESR after thermal vacuum testing might have been due to the fact that thermal vacuum testing promoted the escape of trapped water vapors from the epoxy molding. Visual inspection after the test did not reveal any detectable damage.

The thermal vacuum test results are consistent with those of the outgassing test. It appears that performance deterioration will not be a concern when polymer capacitors are placed in a vacuum environment.

## V. Summary

The reliability of PA capacitors with stacked and laminated structures was evaluated using highly accelerated testing (HAT) at different temperatures and voltages. All of the PA capacitors that were tested exhibited a typical Weibull slope parameter  $\beta$  of around 1.5~2.2, indicating a slow wearout failure mechanism that is different from that of Ta polymer capacitors.

Both Ta polymer and PA capacitors have similar temperature accelerating factor values. However, the voltage accelerating factors of PA capacitors are much higher than those of Ta polymers. A high voltage accelerating factor usually means that the capacitor's reliability is more dependent on the applied voltage. This actually is good news for high-reliability applications since a significant amount of extra lifetime reliability can be attained if a capacitor with a high accelerating voltage factor value is slightly voltage de-rated.

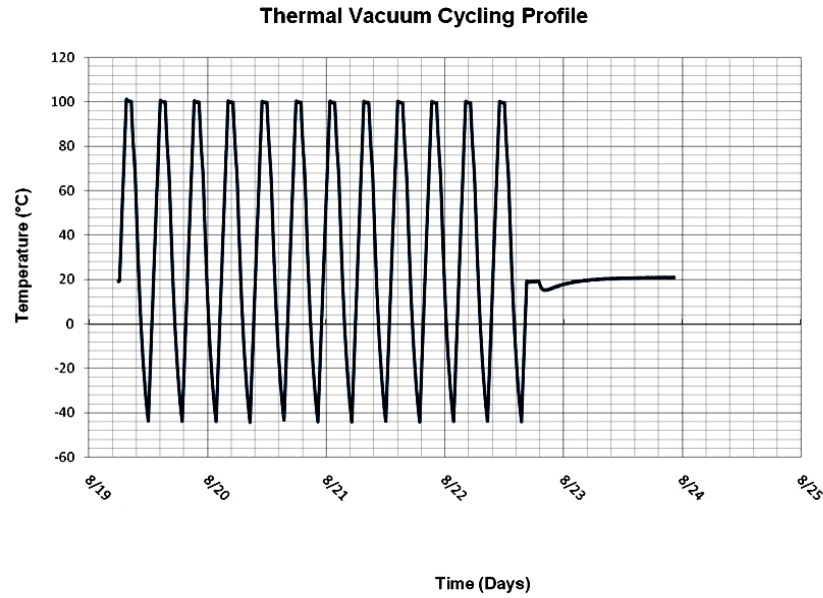
The calculated use-level *MTTF* is at least  $10^4$  years for Ta-poly capacitors and  $10^6$  years for PA capacitors. Both *MTTF* values are good enough for most space applications.

This sample of polymer capacitors meets the minimum outgassing requirements. The impact on the electrical performance of Ta and PA capacitors before and after thermal vacuum cycling is negligible.

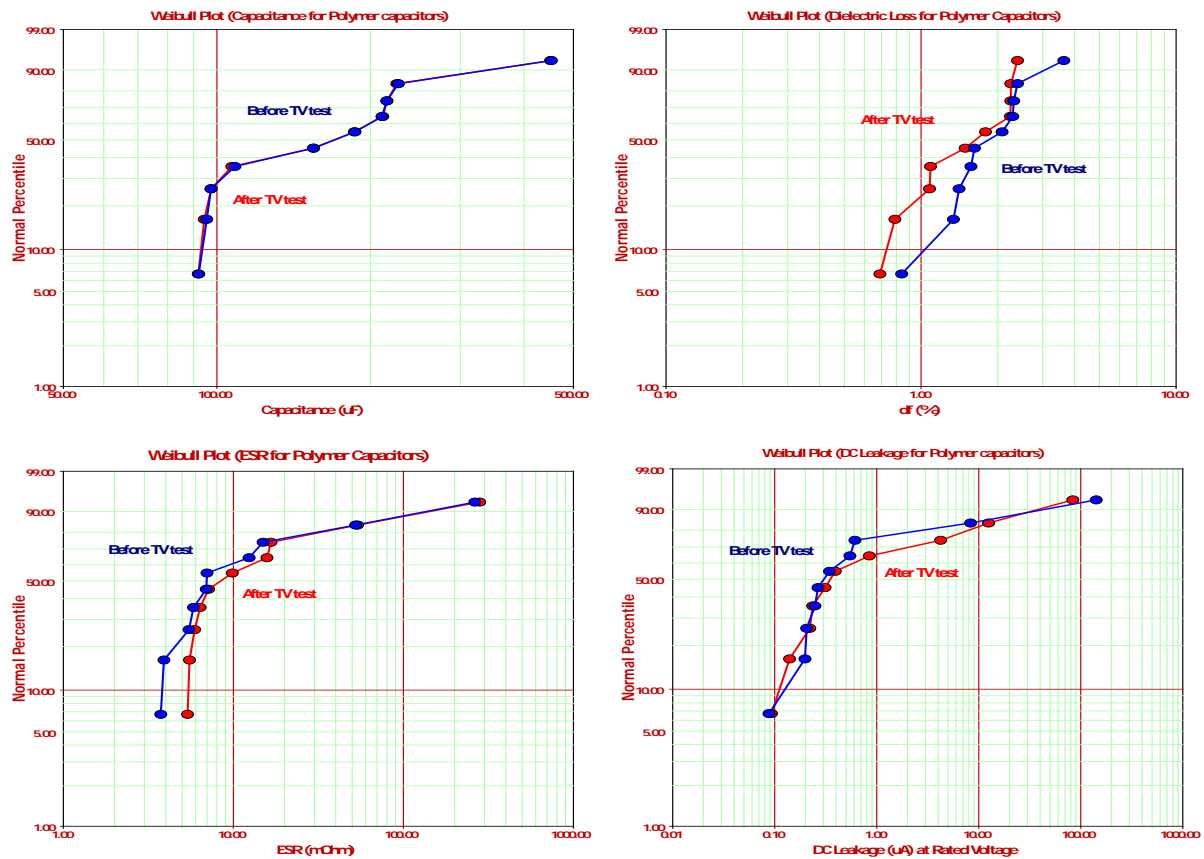
The test results reported in study, together with the physical and electrical characterization results from a previous study, suggest that PA capacitor technology is worthy of further study as a candidate technology for future NASA applications.

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**Figure 4.** Thermal vacuum cycling profile used in this study.



**Figure 5.** Weibull plots of capacitance,  $df$ , ESR, and DC leakage of capacitors before and after thermal vacuum testing.



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